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Coplanar Ternary Decay of Hyper-deformed ^{56}Ni

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Ternary fission events from the decay of ^{56}Ni compound nuclei, formed in the ^{32}S + ^{24}Mg reaction at $E_{lab}(^{32}S) = 163.5$ MeV, have been measured in a unique set-up consisting of two large area position sensitive (x,y) gas detector telescopes. Very narrow out-of-plane correlations are observed for two fragments emitted in either purely binary events or in events with a missing mass consisting of 2 and 3 α-particles. These correlations are interpreted as ternary fission decay from compound nuclei at high angular momenta through an elongated (hyper-deformed) shape with very large moments of inertia, where the lighter mass in the neck region remains at rest.

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Clustering and large deformations are observed as general phenomena at low excitation energy in light N=Z nuclei. They are also predicted at higher excitation energies and at high angular momenta in nuclei with masses ranging from A = 20 up to 100. Of particular interest are the highly deformed shapes as discussed in various theoretical approaches [1–6]. The structure of these configurations is strongly influenced by clustering and the corresponding fission into clusters is expected to dominate, in particular at high angular momentum. In these nuclei energetically favoured states with super- and hyper-deformed shapes, i.e. with quadrupole deformation parameters β_2=0.6-1.0 (corresponding to major-to-minor axis ratios of 2:1 up to 3:1, respectively for ellipsoidal deformation) are predicted with the Nilsson-Strutinsky method [3–6]. The deformed shell corrections also stabilize the rotating nucleus in its hyper-deformed shape at high angular momentum [5]. Similar configurations are obtained in an α-cluster model [2], highlighting the relation between large deformations and clustering. Furthermore, ternary fission is predicted for many such nuclei using a generalised liquid drop model, taking into account the proximity energy and quasi-molecular shapes (as in the cluster models) by Royer et al. [7, 8] for ^{56}Ni and ^{48}Cr nuclei. The ternary fission process can be strongly enhanced for the largest deformations due to the lowering of the fission barrier by the aforementioned shell corrections. However, until now no experimental evidence for such ternary break-up of the light nuclei has been reported [9]. Searches for hyper-deformation in heavier nuclei via γ-decay at high angular momentum [10] have shown that its identification is a very difficult task, because of the increased competition with fission decay.

We have studied fission events from the decay of the ^{56}Ni compound nucleus (CN) at an excitation energy of $E^*_{CN} = 83.97$ MeV, formed in the ^{32}S+^{24}Mg reaction at $E_{lab} = 163.5$ MeV, by measuring two fragments in coincidence. The binary decay in the ^{32}S+^{24}Mg system has been studied extensively by Sanders et al. [11] using kinematical coincidences. From this pioneering work some basic information on the CN formation is available. For instance, the maximum angular momentum reached for ^{56}Ni, is close to 45$\hbar$, consistent with the predicted liquid-drop limit [12] and, at these high angular momenta the binary fission decay can reach up to 10% of the total fusion cross section. We will show that the ternary fission decay in this nucleus competes with the binary fission at high angular momentum due to the formation of hyper-deformed configurations.

The present experiment was performed at the VIVITRON Tandem facility of IReS (Strasbourg), with the BRS-EUROBALL set-up [13–15] aimed at particle-γ-spectroscopy. Two detector telescopes, labelled 3 and 4, are placed symmetrically on either side of the beam axis and comprise two-dimensional position-sensitive low-pressure multi-wire chambers (MWC) and Bragg-curve ionisation chambers. In the reaction, schematically written as $(M_1, Z_1)+(M_2, Z_2) \rightarrow {}^{56}\mathrm{Ni}^* \rightarrow (M_3, Z_3)+(\Delta Z)+(M_4, Z_4)$, two heavy fragments with masses (M_3, M_4) and charges (Z_3, Z_4) are registered in kinematical coincidence and identified by their charges, The masses could not be fully determined in this experiment, details of the detectors and the experimental set-up are given in [16]. Correlations have been measured between two heavy ejectiles with respect to in-plane and out-of-plane scattering angles, θ and ϕ, respectively. Other parameters measured are the Bragg-peak height BP, the range R and the rest energy E, giving the identification of the fragments by their charge and momentum vectors. Two typical BP versus R spectra have been shown in Fig.1 of [15] for the ^{24}Mg+^{12}C reaction measured with the same set-up. The two detectors cover in-

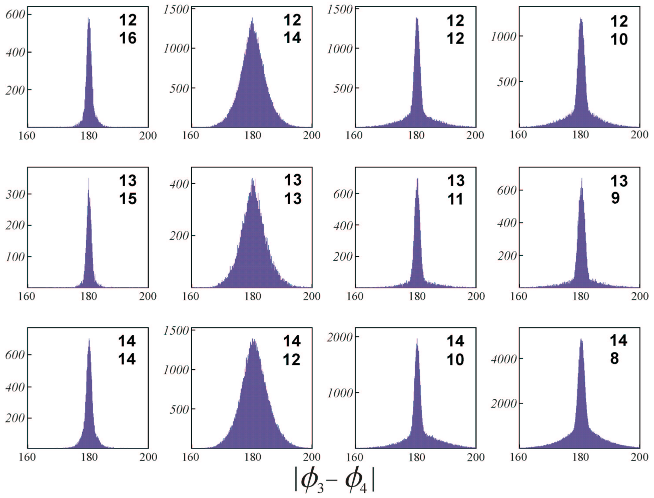

FIG. 1: Yields (counts), $N(Z_3, Z_4)$, of coincident fragments with charges Z_3 and Z_4, as indicated, as a function of $|\phi_3 - \phi_4|$, in degrees, showing the out-of-plane angular correlations for binary decay (col.1) and for the respective non-binary emission channels with missing ΔZ $= 1\alpha$, 2α(col.3), and 3α (col.4) in the reaction ^{32}S + ^{24}Mg at $E_{lab} = 163.5$ MeV.

plane angles $\theta = 12.5° - 45.5°$, and in their centre planes the out-of-plane angles ranges are $\Delta\phi = 0° \pm 16.8°$, or $180° \pm 16.8°$. The x- and y-read-outs of the detector yield the angles, θ and ϕ, of the fragments. Reaction channels are defined by the the sum of the observed charges of the fragments, (Z_3 + Z_4). This procedure gives information for channels with a well defined missing charge ΔZ=(Z_{CN} − Z_3 − Z_4) in the range (ΔZ = 0 - 8). For binary exit channels with two excited heavy fragments which evaporate particles, very broad out-of-plane (ϕ) distributions are expected, because of the missing information on the unobserved (evaporated) particles.

For the following discussion of ternary events these out-of-plane correlations are of importance. The reaction plane is spanned by the beam axis and the vectors of the two detected fragments, and the difference (ϕ_3 − ϕ_4)=180° defines coplanarity. These fragment yields, $N(Z_3, Z_4)$, are plotted in Fig. 1 for different combinations of Z_3 and Z_4, but with *even total charge*, Z_{total}, and different ΔZ. The coplanarity condition is fulfilled for binary events in the form of a narrow peak. No narrow correlation is observed for ΔZ = 2, as expected, where the corresponding recoil of the evaporated α-particles widens the angular correlation (see Fig. 1). These events are originally from binary fission with a very large yield corresponding to an excitation energy in either fragment sufficiently high for one α-particle emission to occur.

For the *binary* decay processes (defined by ΔZ= 0) for different mass splits (col.1 of Fig. 1), the out-of-plane angular correlations are sharp, with a small broad component, which must result from neutron evaporation. The expectation is that for larger charge losses $\Delta Z > 0$ (a sequential emission of several charged particles) the (ϕ_3, ϕ_4)-correlations have increasing width. This is only partially fulfilled with a broad component, e.g. for ΔZ= 4, two missing α-particles (col.3 in Fig. 1). Surprisingly, a very narrow component, as sharp as in the binary case, is observed together with a broad component. The narrow correlation pattern continues to appear for the cases of three missing α-particles (col.4 in Fig. 1), but not for four, where the very negative Q-value does not allow a ternary fission process. We will show that these facts can be consistently described by the competition between binary and ternary decays. In the latter the missing α-particles remain at rest in the the centre-of-mass system. For all correlations with *odd total charges* no such narrow peaks appear. The result also indicates that the missing particles are multiples of α-clusters. Such behaviour is predicted by the α-cluster model (see third diagram of Fig. 3 in [2]) for the hyper-deformed ^{56}Ni at high angular momentum.

The narrow correlations can originate from different mechanisms.

i) Pre-fission emission: a fission process after emission of nucleons or of one or two (and even more) α-particles. Such pre-scission process will not disturg the correlation of the two remaining fission fragments. We can rule out this process by the following arguments. The CN decays mainly by particle evaporation, consistent with the systematics of Morgenstern [17], that the average energy carried by one nucleon is 16.4 MeV and by one α-particle is 23.4 MeV. In the emission of one nucleon or α-particle this amount of energy or more must be removed, and it is known *no second chance fission* can be expected [11, 18]. Indeed, no significant contribution from a narrow peak in the (ϕ_3, ϕ_4)-correlations is observed for the fragment-fragment coincidences with one missing charge or for ΔZ=2.

ii) A binary fission process: e.g. with ΔZ= 4 - for which two α-particles are emitted, the latter must be emitted correlated in-plane from two primary heavy ejectiles, with their angular momenta strongly aligned perpendicular to the reaction plane. The complete correlation from the first step has to be preserved for the whole set of data. The fact that narrow correlations still appear for ΔZ= 4, 6 (also in [16]) makes it rather unlikely that such a special correlation is created and persists through all decays.

iii) Ternary fission: the missing charges (several α-particles), remain at rest in the centre-of-mass frame with the formation of a neck. This process produces a narrow (ϕ_3, ϕ_4)-correlation as in a binary decay, because the neck-particles carry no (or little) momentum in the centre-of-mass frame. With the third clustered fragments in the neck the two remaining heavier fragments are then emitted in a sharp correlation as in the case of a binary fission process. As explained below, the ternary process can only occur for the highest angular momenta, thus the sum (ϕ_3 − ϕ_4) remains 180°. We note that in an earlier measurement, performed with the BRS-spectrometer for the reaction ^{36}Ar+^{24}Mg(CN = ^{60}Zn) at E_{lab} = 195 MeV, under similar conditions the same unique narrow correlations with $\phi_3 - \phi_4 = 180°$ have been observed [16].

A major point in the interpretation of the data is to explain the very strong yield of the "ternary" fission channels relative to the binary decay. For the interpretation of the data as a ternary fission process, we have to consider the statistical phase space for both binary and coplanar ternary fission. This can be achieved by considering the Extended Hauser-Feshbach Method (EHFM) [18]. For ternary events, implying Nα-particles in the neck, remaining without momentum, we will disregard the phase space of these particles, as well as their kinetic energy. For a CN with excitation energy, E^*_{CN}, a ternary Q-value $Q_{gs}(3,4)$, and excitation energies of the fragments given by U_3, U_4, with their relative kinetic energy as $E_{kin}(3,4)$, we have the constraint: $U_3 + U_4 = E^*_{CN} + Q_{gs}(3,4) - E_{kin}(3,4)$. The two excitation energies are connected via the energy conservation and both fragments being registered in coincidence before further decay, their excitation energies, U_3 and U_4, are below the α-decay threshold, which for even-even nuclei with (N=Z) is in the region of 5-8 MeV.

The differential decay cross section for different mass partitions (i,j) depends on the *product of the level densities* $\rho_i(U_i, J_i)$, for $i = 3, j = 4$ and on the inverse fusion cross section $\sigma(E_{kin}(3,4), R_s, J)$

$$\frac{d\sigma(3,4)}{d\Omega dE_{kin}(3,4)} = C\rho_3(U_3, J_4)\rho_4(U_3, J_4)\sigma(E_{kin}(3,4)R_s, J)$$

J_3 and J_4 are the spins of the fragments (with total spin J), and R_s stands for the shape of the saddle. For the total energy balance, with potential energy $V^{eff}_{pot}(J,3,4,R_s)$, which includes the rotational energy, we have for the free energy, :

$$E_{free}(3,4,J) = E^*_{CN} + Q(3,4) + V^{eff}_{pot}(J,3,4,R_s)$$

which will determine the yield for a particular partition. The rotational energy $E_{rot}(J,3,4,R_s)$ depends on the total spin J and on the moment of inertia $\Theta_{ff}(R_s)$, and finally the total potential contains the shell corrections $\Delta_{sh}(R_s)$ at the deformed saddle point: $V^{eff}_{pot}(J,3,4,R_s) = E_{rot}(J,3,4,R_s) + V_{pot}(3,4,R_s) + \Delta_{sh}(R_s)$. These values of the shell corrections for hyper-deformed shapes are in the range of 5-8 MeV for N=Z=28, and can be found in the review [6]. Using this approach, the interpretation of the relative yields of the binary and ternary fission yields can be obtained using the statistical model, these depend on: a) the different Q-values, and therefore on the different values of $E_{free}(3,4,J)$ and thus differences in U_i, b) the shell corrections for large deformations (3:1 axis ratio), c) the angular momentum through the different moments of inertia Θ_{ff}, and corresponding fission barrier heights. Some relevant values are summarised in Table I).

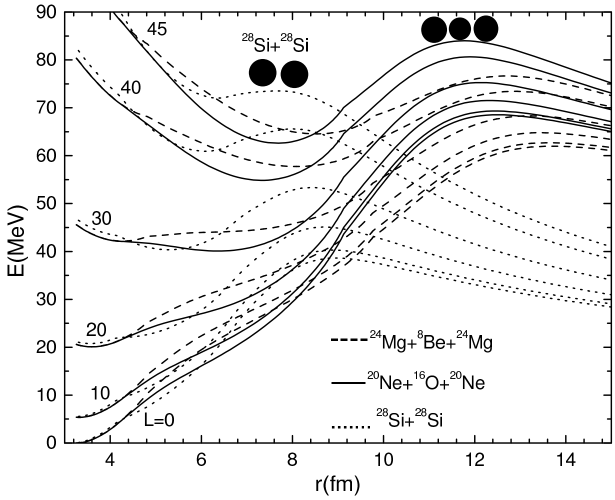

FIG. 2: Potential energies for selected fragmentations in the decay of ^{56}Ni as a function of the deformation (represented by the distance r between the two heavier fragments) for different angular momenta (in units of $\hbar$) for binary and ternary fission, respectively. Channels with different ΔZ, (missing 2 and 4α-particles) are shown. The Q-value for, ^{28}Si+^{28}Si is +3.04 MeV, for the ^{8}Be channel, Q= −16.9 MeV.

TABLE I: Q-values, the inverse of the moments of inertia ($\hbar^2/\Theta_{ff}$) and barrier heights for some fission channels of ^{56}Ni.

Q-value	Mass split	$\hbar^2/\Theta_{ff}$	Barrier(J=45)
MeV	*Binary* (− 0α)	MeV	MeV
+3.04	^{28}Si + ^{28}Si	0.038	73.5
−2.67	^{20}Ne + ^{36}Ar	0.041	75.7
−10.3	^{22}Na + ^{34}Cl	0.040	74.7
MeV	*Ternary* (− 2α)		
−16.93	^{24}Mg+2α+^{24}Mg	0.015	76.6
−14.04	^{32}S + 2α + ^{16}O		
MeV	*Ternary* (− 3α)		
−26.24	^{24}Mg+3α+^{20}Ne	0.014	78.9
−20.99	^{28}Si + 3α + ^{16}O		
−35.88	^{26}Al + 3α + ^{18}F		

In the calculations by Royer [8], the liquid drop energies, the Q-values and the rotational energies constitute the main part of the barrier heights for the fission process. With the angular momentum dependence of $V^{eff}_{pot}(J,3,4,R_s)$, the free energy $E_{free}(3,4,J)$ at the saddle point is dramatically reduced for both the binary and the ternary mass splits as a function of J, the latter barrier becomes comparable to the former, the negative Q-value being compensated by the smaller value of $E_{rot}(J,3,4,R_s)$. In Table I we show the Q-values and the rotational energies at the saddle point for $J = 45\hbar$, which will determine the penetrabilities. The Q-values are more negative for ternary mass splits, therefore negligible contributions are expected at low angular momentum. For the case of ternary fission with ΔZ=8 the barriers are so high that no ternary fission becomes possible. As shown in Fig. 2 and Table I the barriers for binary and ternary

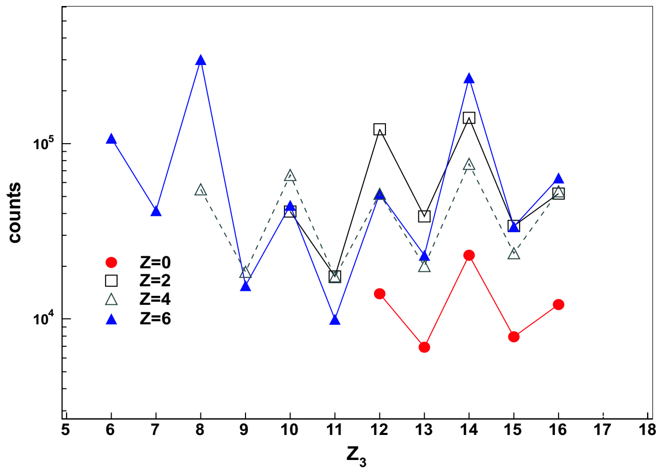

FIG. 3: Yields of binary ($\Delta Z = 0$) and ternary coincident fission fragments, the respective non binary emission channels are with missing ΔZ= (2)-1α,(4)-2α, and (6)-3α-particles from the reaction ^{32}S +^{24} Mg at E_{lab} = 163.5 MeV.

fission become comparable only at the highest angular momenta. The Q-values for the ternary mass splits with odd-odd charge fragments are in addition 5-10 MeV more negative. Thus, in these cases much lower yields and less subsequent decays via particle evaporation are possible. In fact the narrow peaks in the (ϕ_3, ϕ_4)-correlations dominate the spectra if the sum of two odd charges is taken (Fig. 1, middle row).

Following these considerations the ternary fission process can be found to favourably compete with the binary mass split only at high angular momentum, around 45$\hbar$, because of the increased moments of inertia Θ_{ff}, of the hyper-deformed states. In addition, this effect is supported by the shell corrections to the liquid-drop energy of approximately 5-8 MeV [6]. The relative yields shown in Fig. 3 confirm the the statistical-model predictions, i.e. the odd-even effect in the yields is clearly observed. The high yield for the $^{28}\mathrm{S} + ^{12}\mathrm{C} + ^{16}\mathrm{O}$ channel with $(Z_3 + Z_4 = 8 + 14)$ is striking, because it exceeds the binary decay. This can be explained by the decay of a hyper-deformed resonant state, which is known at exactly the chosen excitation energy in the ^{56}Ni nucleus (populated due to the choice of the incident energy on top of a ^{28}Si+^{28}Si resonance, described in Refs. [2, 20]. The ternary fission process from the hyper-deformed configuration is enhanced due to a lowering of its ternary fission barrier. The neck represents a region of low nuclear density favouring the formation of α-clusters as recently discussed by Horiuchi [19].

We conclude that the observation of the narrow coplanar fission-fragment coincidences in the present data, in conjunction with the earlier work on the same phenomenon in Ref. [16], is a unique feature, which gives evidence for the occurrence of ternary decay processes. This work also shows that the search for hyper-deformation, in rapidly rotating nuclei, can be pursued with charged-particle spectroscopy. For nuclei in the medium-mass region a complete reconstruction of the ternary fission events can be undertaken with appropriate detector systems. Thus, measurements of the ternary fission process offer the possibility of detailed spectroscopy of extremely deformed nuclear states.

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